

The Nearshore Benthic Invertebrate Community of Southern Lake Michigan and its Response to Beach Nourishment

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ABSTRACT. *The nearshore benthic environment of Lake Michigan represents a dynamic and little studied habitat. To explore the biology and response of this community to beach nourishment, Ponar samples were taken at 1.5, 3, and 6 m depths at 10 transects along the southern shore of Lake Michigan before and after beach nourishment. Forty taxa were identified, and two of these, Chaetogaster diastrophus and Nematoda, made up over 81% of all organisms collected. Shallow sites (≤ 3 m) were generally dominated by C. diastrophus and Nematoda, and these sites represent communities adapted to constant wave induced sediment disturbance. Deep (6 m) sites were generally dominated by Nematoda, but fair numbers of C. diastrophus, Amphichaeta leydigi, Paracladopelma spp., and other less abundant taxa were identified. Greater diversity at deeper sites may be related to the stability resulting from reduced wave disturbance. A notable decrease in mean invertebrate density ($P < 0.01$) from 2001 to 2002 downdrift from the site of beach nourishment suggests that sand placement affected invertebrate populations, although a more thorough understanding of this community's response to environmental variables is required to further support this conclusion.*

INDEX WORDS: *Sand, coastal, disturbance, macrobenthos, meiobenthos, Great Lakes.*

INTRODUCTION

The present day coast of the southern tip of Lake Michigan represents a dynamic aquatic ecosystem. Sediment, which consists primarily of sand, is pushed predominantly south along the eastern and western shores by wind and waves, converging along the Indiana shoreline (Chrzastowski and Thompson 1994). While the lake basin serves as a sink for some of these sediments, roughly half are deposited on the beaches and dunes of southern Lake Michigan (Colman and Foster 1994). Along the southern shore, weather influences the movement, sorting, and deposition of aquatic sediments (Thompson 1989), and severe weather may impact the nearshore area to depths of 25 m (Booth 1994).

Construction of breakwaters in Michigan City Harbor, Indiana, has trapped or diverted much of the sand that would otherwise move west along the shoreline (Shabica and Pranschke 1994). This interruption of the sediment transport cycle has caused the beaches of Indiana Dunes National Lakeshore, which lie west of Michigan City Harbor, to become sediment starved and suffer erosion. Nourishment with sediments transported from other areas is a common solution to beach erosion (Peterson *et al.* 2000), and sand has been deposited on the beaches of the Indiana Dunes for more than two decades (Felicia Kirksey, U.S. Army Corps of Engineers, personal communication on 2 January 2003). Most recently, in mid-August of 2001, the Corps of Engineers deposited roughly 33,000 m³ of sand on the shore by Mt. Baldy, a popular tourist destination at the east end of the Indiana Dunes. Some, although

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not all, of this sand is washed into Lake Michigan by wind and wave action.

The habitat in the study area is fairly homogeneous, being composed chiefly of shifting sand with little organic matter, although in some areas sediment starvation has caused the exposure of underlying clay. Nearshore sand invertebrate communities in Lake Michigan have received little attention (Whitman *et al.* 1994, Horvath *et al.* 2001), but work has been done on benthos in deeper offshore waters (Nalepa and Quigley 1983, Nalepa *et al.* 1998). The effects of beach nourishment on benthos has also received little attention (Peterson *et al.* 2000), and no references to research on the effects of beach nourishment on freshwater invertebrates were found. The 2001 beach nourishment site at Mt. Baldy, Indiana Dunes National Lakeshore was used to survey the biology of the wave-impacted, nearshore benthic community and to investigate its response to beach nourishment.

METHODOLOGY

Ten transects extending approximately perpendicular to the shoreline were selected, each with sampling sites at the 1.5, 3, and 6 m depth contours (Fig. 1). All were within 400 m of shore. One sample was collected from each of the 30 sites using a petite Ponar sampler (225 cm²) on 31 July 2001 and 9 August 2002. A Garmin GPS III Plus was used to relocate transects and sites the second year of the study. Most samples contained only sand, although a few contained sand mixed with fine silt or clay. Samples were stored in lake water in plastic sample jars for roughly 2 hours before further processing was done in the laboratory. To separate invertebrates from sediments, samples were swirled rigorously to suspend invertebrates in the sample water and this water was poured through a 106 µm mesh sieve (Horvath *et al.* 2001). Tap water was added to samples, the above procedure was repeated two more times, and organisms retained by the sieve were preserved with 90% ethanol.

Final separation of invertebrates from remaining sediment was done in gridded counting dishes. Due to their abundance, nematodes and oligochaetes were sometimes subsampled prior to enumeration. For nematodes, a random number table was used to select ten squares from which they were picked and enumerated. For oligochaetes, random squares were chosen and picked until at least 50 intact organisms were found, and these organisms were identified. Invertebrates were separated from remaining sedi-

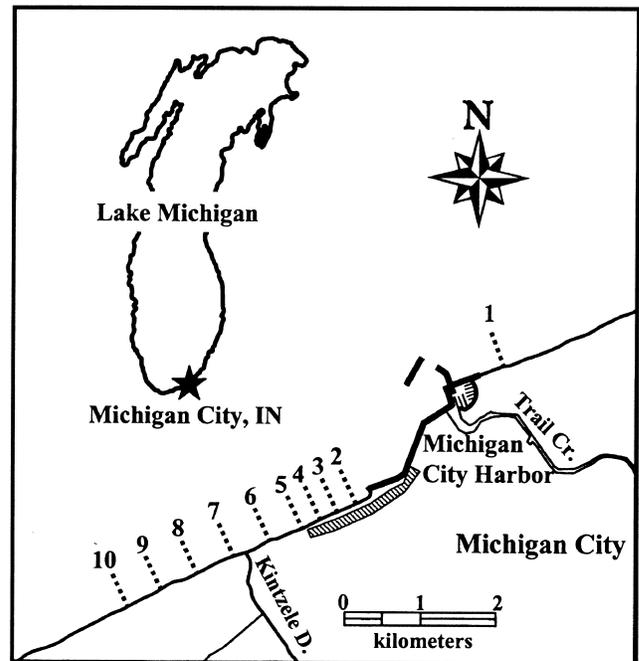


FIG. 1. Samples were collected along labeled transects at the 1.5, 3, and 6 m depth contours, and beach nourishment occurred in the cross-hatched area.

ment under magnification using an Olympus SZ60 stereo-microscope and were identified using an Olympus BH2 compound microscope. Glycerine jelly was used as a general-purpose mounting medium, and when more permanent mounts were desired, CMCP-10 was used. When necessary, chironomid heads were cleared using a 50% solution of lactic acid.

Although plankton was occasionally collected, only benthic animals were included in the analysis. Nematodes (phylum Nematoda), flatworms (order Microturbellaria), leeches (class Hirudinea), water bears (phylum Tardigrada), aelosomatids (family Aelosomatidae), clams (family Sphaeriidae), ostracods (class Ostracoda), and mites (order Acariformes) were left at these taxonomic levels for analysis. Oligochaetes were identified to species using Kathman and Brinkhurst (1999), copepods were identified to species using Hudson and Lesko (2002), and chironomids were identified to genus according to Coffman and Ferrington (1996). An unidentified species of harpacticoid copepod resembling the marine *Heteropsyllus nunni* was found (Horvath *et al.* 2001, Hudson and Lesko 2002) and this taxon will be referred to as *Heteropsyllus* sp.

hereafter. Number of individuals sample⁻¹ was converted to number of individuals m⁻² and is hereafter reported as mean m⁻² ± SE.

The outflow of Kintzele Ditch lies within the study area (Fig. 1), so it was deemed important to gauge its flow during sampling years. Because no monitoring station exists on this stream, the flow of Trail Creek, which flows into Lake Michigan only 1.5 km further east, was used for comparisons under the assumption that discharge from the two streams would be roughly proportional due to the proximity of their watersheds. Analysis of the variation in offshore wind speed and wave intensity between the two years was also undertaken using data collected from Station 45007 of the National Data Buoy Center, National Oceanic and Atmospheric Administration.

SPSS v. 11.5 was used for comparative statistics (SPSS 1999), and data were Log₁₀ (x + 1) transformed to meet the assumption of normality. ANOVA with Tukey's b as a post hoc test and independent samples T-tests were used when data met assumptions of normality and equal variance; when either of these were violated, non-parametric equivalents were used. Spearman's rho or Pearson's correlation coefficient were used when correlations were investigated depending on whether data could be normalized. Primer v. 5 was used to compute Shannon-Wiener diversity and Pielou's evenness values (Clarke and Warwick 1994, Clarke and Gorley 2001).

RESULTS AND DISCUSSION

Community Characterization

Booth (1994) noted that depths to 5 m are influenced by wave action during normal weather conditions, and depths up to 25 m can be influenced during severe weather. Much of the present study area, particularly the 1.5 and 3 m sites, lies within the depth range that would be continually disturbed by wave action, thus allowing only the most disturbance-tolerant organisms to persist. In other wave-impacted areas of the Great Lakes, benthic communities relate to exposed rock or macrophytes (Barton and Carter 1982). The constantly shifting sands of southern Lake Michigan, however, provide little natural, permanent structure to which benthic organisms can attach or relate, thus limiting species diversity.

Forty taxa were identified in this study, and their densities, maximum occurrence, and relative abun-

dances are presented along with total invertebrate density (Table 1). Total invertebrate densities ranged from a minimum of 356 individuals m⁻² in 2002 to a maximum of 79,360 invertebrates m⁻² in 2001, although most measurements were above 15,000 individuals m⁻². These densities are low compared to some studies that sampled further offshore (Nalepa and Quigley 1983) but within the range commonly reported for the nearshore zone of the Great Lakes (Barton and Carter 1982, Barton and Griffiths 1984). Two taxa, *Chaetogaster diastrophus* and Nematoda, dominated the nearshore benthic environment, with relative abundances of most other taxa less than 1%. Whitman *et al.* (1994) noted the occurrence of only nematodes and oligochaetes in the swash zone of a beach at the southern tip of Lake Michigan, and these taxa represented over 90% of the organisms collected at < 3 m in this study.

Mean density, diversity, number of taxa, and taxa evenness at 1.5, 3, and 6 m depths were calculated for both 2001 and 2002 (Table 2). In 2001 positive correlations between depth and diversity (P < 0.01), number of taxa (P < 0.01), and taxa evenness (P < 0.05) were significant, and while 2002 densities appeared to decrease with increased depth, this correlation was not significant. Many taxa exhibited either statistically significant or apparent depth preferences (Table 3). Relative abundance of nematodes increased from 21.4% at shallow sites to 51.5% at the 6 m site, while that of *C. diastrophus* decreased to 15.3% as depth increased. Another oligochaete, *Amphichaeta leydigi*, increased in relative abundance from less than 1% at shallow sites to 12.2% at 6 m sites. The oligochaetes *Piguetiella blanci*, *P. michiganensis*, *Paranais frici*, *Vejdovskyella intermedia*, *Uncinaiis uncinata*, and tubificids were only collected at 6 m depths. The increase with depth seen among oligochaetes and other benthic invertebrates suggests that the wave-induced disturbance of the shallows constrains the number of taxa that can persist in this environment, and this relationship has been observed in other studies (DeFelice and Parrish 2001).

The shift from a shallow community dominated by *C. diastrophus* and Nematoda to a deeper (6 m) community in which dominance is shared among a greater number of taxa is noteworthy. Considering that many taxa identified in this study are part of the detrital food web (Thorp and Covich 1991, Coffman and Ferrington 1996), the increased stability afforded by deeper water may indirectly bring about this community shift by permitting a slightly

TABLE 1. Mean and maximum densities and relative abundances (%) of taxa collected from the nearshore zone in 2001 and 2002. Densities of bolded taxa differed significantly between years at the $P < 0.05$ level.

Taxa	2001			2002		
	Mean \pm SE	Maximum	Rel. abund.	Mean \pm SE	Maximum	Rel. abund.
Nematoda	9,519.9 \pm 1,171.2	21,511.1	34.8	1,798.5 \pm 463.8	13,066.7	17.04
Tardigrada	13.3 \pm 7.1	177.8	0.05	0	0	0
Hirudinea	17.8 \pm 10.9	311.1	0.06	56.3 \pm 22.9	577.8	0.53
Aelosomatidae	294.8 \pm 124.3	2,666.7	1.08	42.9 \pm 27.2	800	0.41
<i>Amphichaeta leydigi</i>	842.9 \pm 294.2	5,511.1	3.08	499.3 \pm 228.4	5155.5	4.73
<i>Chaetogaster diastrophus</i>	12,902.2 \pm 2,457.9	60,666.6	47.16	7,066.7 \pm 2,352.8	60,799.9	66.95
<i>Nais variabilis</i>	102.2 \pm 44.5	888.9	0.37	65.2 \pm 30.9	800	0.62
<i>Paranais frici</i>	77.0 \pm 40.9	1,022.2	0.28	1.5 \pm 1.5	44.4	0.01
<i>Piguetiella blanci</i>	4.4 \pm 4.4	133.3	0.02	1.5 \pm 1.5	44.4	0.01
<i>Piguetiella michiganensis</i>	26.7 \pm 26.7	800	0.1	0	0	0
<i>Uncinaiis uncinata</i>	0	0	0	69.6 \pm 36.9	800	0.66
<i>Vejdovskyella intermedia</i>	31.1 \pm 21.6	488.9	0.11	0	0	0
Tubificidae	14.8 \pm 11.1	311.1	0.05	8.9 \pm 7.5	222.2	0.08
Microturbellaria	600.0 \pm 146.2	3,555.6	2.19	71.1 \pm 31.4	666.7	0.67
Sphaeriidae	585.2 \pm 140.9	3,777.8	2.14	74.1 \pm 25.6	533.3	0.7
Ostracoda	5.9 \pm 3.5	88.9	0.02	0	0	0
<i>Acanthocyclops brevispinosus</i>	53.3 \pm 11.4	222.2	0.19	65.2 \pm 53.2	1,600	0.62
<i>Diacyclops nanus</i>	0	0	0	2.9 \pm 2.1	44.4	0.03
<i>Eucyclops agilis</i>	4.4 \pm 3.3	88.9	0.02	1.5 \pm 1.5	44.4	0.01
<i>Paracyclops chiltoni</i>	1.5 \pm 1.5	44.4	0.01	0	0	0
<i>Nitocra hibernica</i>	50.4 \pm 29.5	844.4	0.18	0	0	0
<i>Canthocamptus robertcokeri</i>	11.9 \pm 4.2	88.9	0.04	11.9 \pm 7.4	177.8	0.11
<i>Heteropsyllus nunni</i>	293.3 \pm 118.5	3,244.4	1.07	56.3 \pm 23.6	577.8	0.53
<i>Schizopera borutzkyi</i>	204.4 \pm 125.6	3,777.8	0.75	2.9 \pm 2.1	44.4	0.03
Acari	2.9 \pm 2.1	44.4	0.01	4.4 \pm 2.5	44.4	0.04
<i>Apedilium</i> spp.	2.9 \pm 2.9	88.9	0.01	0	0	0
<i>Axarus</i> spp.	4.4 \pm 3.3	88.9	0.02	1.45 \pm 1.5	44.4	0.01
<i>Chironomus</i> spp.	189.6 \pm 41.2	755.6	0.69	14.8 \pm 5.8	133.3	0.14
<i>Cladotanytarsus</i> spp.	69.6 \pm 21.7	400	0.25	0	0	0
<i>Cryptochironomus</i> spp.	31.1 \pm 10.3	177.8	0.11	23.7 \pm 7.9	133.3	0.22
<i>Heterotrissocladius</i> spp.	16.3 \pm 6.6	133.3	0.06	14.8 \pm 6.2	133.3	0.14
<i>Monodiamesa</i> spp.	7.4 \pm 6.1	177.8	0.03	7.4 \pm 3.7	88.9	0.07
<i>Orthocladius/Cricotopus</i> spp.	0	0	0	1.5 \pm 1.5	44.4	0.01
<i>Parachironomus</i> spp.	0	0	0	1.5 \pm 1.5	44.4	0.01
<i>Paracladopelma</i> spp.	968.9 \pm 161.6	3,911.1	3.54	487.4 \pm 73.7	1,733.3	4.62
<i>Polypedilum</i> spp.	75.6 \pm 30.5	755.5	0.28	63.7 \pm 23.4	622.2	0.6
<i>Psectrocladius</i> spp.	317.0 \pm 144.6	3,288.9	1.16	32.6 \pm 8.8	177.8	0.31
<i>Robackia</i> spp.	0	0	0	4.4 \pm 3.3	88.9	0.04
<i>Tanypus</i> spp.	0	0	0	1.5 \pm 1.5	44.4	0.01
<i>Tanytarsus</i> spp.	16.3 \pm 8.4	222.2	0.06	0	0	0
Total	27,360 \pm 2,547	79,911	100	10,556 \pm 2,354	63,510	100

greater accumulation of organic matter. Significant correlations between amount of detritus and abundance of copepods, oligochaetes and chironomids have been observed in deeper waters (11–17 m) of southern Lake Michigan (Nalepa and Quigley 1983), offering further support to the idea that lack

of organic matter may influence nearshore community composition.

Exotic Species

Among the copepods identified in this study, *Nitocra hibernica*, *Heteropsyllus* sp., and *Schizopera*

TABLE 2. Mean \pm SE invertebrate density, Shannon diversity, number of taxa, and Pielou's evenness in 2001 and 2002 by depth. Bolded values differed significantly ($P < 0.05$) between years.

	2001			2002		
	1.5 m	3 m	6 m	1.5 m	3 m	6 m
Density	25,164 \pm 4,439	31,387 \pm 5,706	25,529 \pm 2,782	12,884 \pm 5,892	12,258 \pm 3,515	6,524 \pm 1,945
Diversity	0.99 \pm 0.09	1.10 \pm 0.10	1.44 \pm 0.13	0.94 \pm 0.14	0.72 \pm 0.10	1.33 \pm 0.09
Number of taxa	8 \pm 1	11 \pm 1	15 \pm 1	7 \pm 1	6 \pm 1	10 \pm 1
Species evenness	0.47 \pm 0.03	0.46 \pm 0.03	0.54 \pm 0.03	0.48 \pm 0.06	0.44 \pm 0.08	0.61 \pm 0.03

borutzkyi are non-native taxa that have invaded the Laurentian Great Lakes (Horvath *et al.* 2001, Hudson and Lesko 2002), and *Heteropsyllus* sp. has maintained its dominance of the copepod community at this study site. *Schizopera borutzkyi*, which was nearly as numerous as *Heteropsyllus* sp. in 2001, declined in 2002 samples, while *N. hibernica* was not identified in 2002. Whether this indicates a shift from a community co-dominated by *Heteropsyllus* sp. and *S. borutzkyi* to one dominated solely by *Heteropsyllus* sp. is unknown at this time. Horvath *et al.* (2001) noted that *Heteropsyllus* sp. was

more abundant in shallower sites (< 9 m) than *S. borutzkyi*, and year-to-year population variation may play a role in the shift in dominance noted in 2002.

Hudson and Lesko (2002) label the *Heteropsyllus* sp. found in the Great Lakes as *Heteropsyllus nunni*, but this species identification is suspect. Pronounced differences in body shape and fifth leg morphology exist between Great Lakes specimens and confirmed specimens of *H. nunni* collected from marine environments along the Atlantic Coast, and the degree of difference suggest that two differ-

TABLE 3. Mean densities $m^{-2} \pm$ SE by depth of taxa with relative abundances $> 0.05\%$. Bolded taxa exhibited depth preferences that were statistically significant at the $P < 0.05$ level. Data from both years of sampling were pooled for this analysis.

	1.5 m	3 m	6 m
Nematoda	2,464.4 \pm 524.1	6,264.4 \pm 1,484.4	8,248.9 \pm 1,612.2
Aelosomatidae	377.8 \pm 180.9	100.0 \pm 51.4	28.9 \pm 24.6
Hirudinea	62.2 \pm 21.7	44.4 \pm 31.1	4.4 \pm 3.1
<i>Amphichaeta leydigi</i>	13.3 \pm 13.3	37.8 \pm 27.6	1,962.2 \pm 435.6
<i>Chaetogaster diastrophus</i>	14,191.1 \pm 3,502.2	13,317.8 \pm 3,157.4	2,444.4 \pm 1,052.2
<i>Nais variabilis</i>	60.0 \pm 43.8	8.9 \pm 6.1	182.2 \pm 63.0
<i>Paranais frici</i>	0	0	117.8 \pm 59.8
<i>Piguetiella michiganensis</i>	0	0	40.0 \pm 40.0
<i>Uncinaiis uncinata</i>	0	0	104.4 \pm 54.2
<i>Vejdovskyella intermedia</i>	0	0	46.7 \pm 32.2
Tubificidae	0	0	35.6 \pm 19.2
Microturbellaria	642.2 \pm 212.3	251.1 \pm 85.9	113.3 \pm 42.8
Sphaeriidae	266.7 \pm 86.2	380.0 \pm 120.7	342.2 \pm 186.9
<i>Acanthocyclops brevispinosus</i>	111.1 \pm 79.2	40.0 \pm 12.9	26.7 \pm 10.9
<i>Nitocra hibernica</i>	2.2 \pm 2.2	13.3 \pm 6.5	60.0 \pm 44.1
<i>Canthocamptus robertcokeri</i>	2.2 \pm 2.2	6.7 \pm 3.6	26.7 \pm 11.4
<i>Heteropsyllus</i> spp.	8.9 \pm 5.2	46.7 \pm 19.5	468.9 \pm 168.5
<i>Schizopera borutzkyi</i>	11.1 \pm 7.1	37.8 \pm 11.3	262.2 \pm 188.6
<i>Chironomus</i> spp.	26.7 \pm 11.8	148.9 \pm 47.9	131.1 \pm 47.7
<i>Cladotanytarsus</i> spp.	0	22.2 \pm 13.9	82.2 \pm 29.8
<i>Cryptochironomus</i> spp.	6.7 \pm 3.6	33.3 \pm 13.6	42.2 \pm 12.3
<i>Heterotrissocladius</i> spp.	8.9 \pm 6.9	13.3 \pm 7.9	24.4 \pm 8.2
<i>Paracladopelma</i> spp.	580.0 \pm 70.6	977.8 \pm 219.2	626.7 \pm 152.9
<i>Polypedilum</i> spp.	22.2 \pm 11.4	15.6 \pm 7.4	171.1 \pm 48.8
<i>Psectrocladius</i> spp.	142.2 \pm 123.8	40 \pm 18.2	342.2 \pm 182.0

ent species are present (Judith Williams, University of Southern Mississippi, personal communication, 25 January 2003). To prevent confusion, the authors suggest that the species be hereafter referred to as *Heteropsyllus* sp. until it is either positively identified or, if new to science, described.

Nourishment Effects

Mean invertebrate density in 2001 prior to beach nourishment was $27,360 \pm 2,547 \text{ m}^{-2}$, and this was significantly higher ($P < 0.01$) than the mean density of $10,556 \pm 2,354 \text{ m}^{-2}$ seen the following year. Additionally, the 11.4 ± 0.7 taxa identified per site in 2001 were significantly more ($P < 0.01$) than the 7.6 ± 0.6 identified in 2002. Differences in Shannon-Weiner diversity and taxa evenness between years were not significant. There were no significant differences in density between transects in 2001 (ANOVA; $P > 0.05$), although differences between transects in 2002 were significant (ANOVA; $P < 0.05$). When log transformed density at each transect was compared between years, significant differences ($P = 0.05$) were seen at transects 2 and 5–9, and a bar graph comparing densities at individual transects in both years illustrates this (Fig. 2). Densities of most taxa were lower in 2002, and these differences were significant for nematodes ($P = 0.05$ at transects 1, 2, 5, 6, 7, 8, and 9), *C. diastrophus* ($P = 0.05$ at 5 and 8), Sphaeriidae ($P \leq 0.05$ at 4, 6, 7, and 9), *S. borutzkyi* ($P < 0.05$ at 5), *Acanthocyclops brevispinosus* ($P < 0.05$ at 5 and 6), Microturbellaria ($P < 0.05$ at 3 and 7), *Paracladopelma* spp. ($P = 0.05$ at 6 and 9) and *Chironomus* spp. ($P < 0.05$ at 7 and 9). Significantly fewer taxa were identified in 2002 at transects 1, 8, 9 ($P = 0.05$), and 7 ($P < 0.05$).

The nearly threefold decline in mean density between 2001 and 2002 suggests substantial changes in the benthic community between the two years. Greatest year-to-year declines were noted at transects 5–9, and while densities of many taxa decreased, nematodes, *C. diastrophus*, and *Paracladopelma* spp. declined the most. Transects 5–9 in 2002 had a significantly higher evenness measure ($P < 0.01$) compared to other transects for that same year and also a higher evenness measure compared to the previous year, and this was likely due to decreases in dominant taxa in 2002 that allowed Pielou's evenness metric to reflect less numerous taxa.

The observed decrease at transects 5–9 in 2002 may signify the negative influence of beach nour-

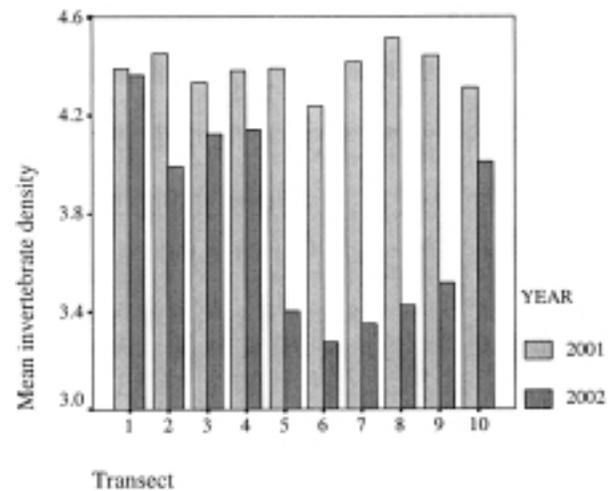


FIG. 2. $\text{Log}_{10}(x+1)$ transformed mean invertebrate densities at each transect in 2001 and 2002. Differences in density were significant ($P = 0.05$) at transects 2 and 5–9.

ishment. Wind and wave action generally push sand toward the southwest along our study area (Chrzastowski and Thompson 1994), so sediments deposited on the beach would be pushed across transects 2–10 (Fig. 1). Sand deposited in August and September of 2001 may have migrated west across the study area, with significant impact measured from transects 5 through 9. The lowest density in 2002 was measured at transect 6, and disturbance by moving sand may have decreased further west as deposited sands mixed with native sands or moved further offshore. It is possible that transect 3 or 4 may have been impacted earlier during the year as deposited sands migrated across them, but recolonization may have occurred prior to sampling in August 2002. Interestingly, while densities at 1.5 and 3 m sites decreased by roughly 50% in 2002, densities at 6 m sites decreased by nearly 75% (Table 2). The disproportional decrease in density at deeper sites from 2001 to 2002 is not understood.

If beach nourishment is the cause of the decreases in invertebrate density noted at transects 2 and 5–9, the precise mode of influence remains unclear. Considering that the substrate is the most important factor governing the composition of benthos, differences in grain size may have altered the substrate characteristics enough to limit the ability of some taxa to persist (Thorup 1964). Sand used to nourish Mt. Baldy was sourced from Aggre-

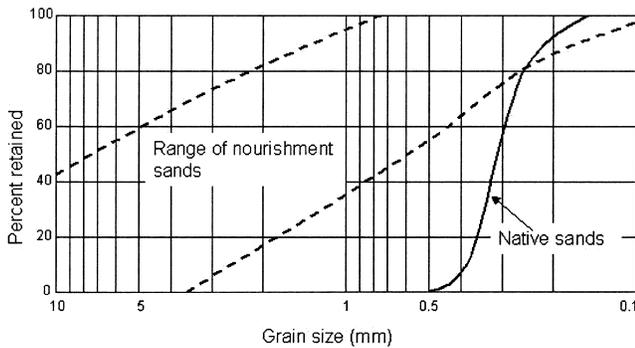


FIG. 3. Grain size distribution of native beach sands (Wood 1983) plotted over the range of grain sizes used for beach nourishment (area between dotted lines).

gate Industries in Kalamazoo, Michigan, and although the grain size distribution of sands used for nourishment was not available, the acceptable grain size range allows for nourishment sediments that are considerably coarser than native sands (Fig. 3). Data on movement of deposited sediments in the study years and changes in mean grain size of nearshore sands were not available, and these data may provide the background necessary to understand better the impact of beach nourishment on the benthic invertebrate community.

Three potentially confounding factors were identified during the course of analysis, including the presence of subsurface clay formations in the area of sampling, the potentially differing effects of wind and waves against the shoreline between the two years, and the effects of a stream that empties into Lake Michigan in the study area. Just offshore of the beach, underlying clay mounds and trenches are sometimes exposed, and these formations have a benthic community distinct from that found in surrounding sands (R. L. Whitman, unpublished data). The clay formations are at their greatest level of exposure and complexity between transects 3 and 8, which conforms fairly well to the pattern of disturbance noted in 2002. Clay was only encountered in one sample in each year however, so it is unlikely that these clay formations caused the changes observed at sampling sites. Further, a permanent feature of the shoreline such as this would be expected to impact invertebrate samples equally in both years.

The action of wind and waves against the shoreline maintains the instability of bottom sediments, and differences between years in wind or wave ac-

tion could confound this analysis. Based on data from Station 45007, a weather buoy in Lake Michigan, shoreward wind speed, wind direction, wave height, and wave direction were averaged by month and compared between years, and no significant differences were seen between 2001 and 2002 ($P > 0.05$). Additionally, transect 1, which was separated from any possible nourishment effects by the break-wall offshore of Michigan City Harbor, showed no significant differences in invertebrate densities between years. Any meteorological events capable of affecting transects 2–10 should have influenced transect 1 as well, making it unlikely that meteorological variation contributed to the decrease in invertebrate density observed in 2002.

Sediment loading and discharge data were not available for Kintzele Ditch, a small stream that empties into Lake Michigan in the area of transects 6 and 7, so stream discharge data from the USGS gauging station of Trail Creek were used to investigate whether discharge could have impacted our 2002 samples. Mean daily discharge rates for Trail Creek are presented (Fig. 4), and mean monthly discharge rates compared between years. February and August discharge rates showed no significant difference between years ($P > 0.05$), while discharge was significantly higher in 2002 in April and May ($P < 0.01$) and lower in 2002 in June and July ($P < 0.01$). While discharge rates in May of 2002 were much higher than in the previous year, any turbulence caused by the outflow of Kintzele Ditch on

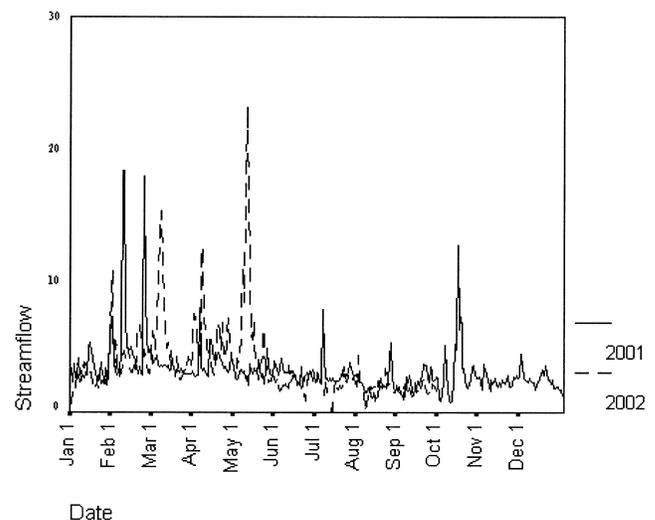


FIG. 4. Discharge rates ($m^3 \text{ sec}^{-1}$) at Trail Creek, a stream that discharges into Lake Michigan roughly 1.5 km east of Kintzele Ditch.

the nearshore area would be negligible relative to that caused by wind and wave action, suggesting that turbulence caused by a high discharge event had no appreciable impact on 2002 samples.

Fair amounts of silt were collected with 6-m samples at transects 1, 3, and 6 in 2002, but since two of these three transects were at least 1 km from the outflow of Kintzele Ditch, and because they all had high populations of *U. uncinata*, an oligochaete generally found in the basin of Lake Michigan, this silt likely originated from elsewhere in the lake rather than from a tributary. Due to dilution and wind-induced currents, the residence time of silt originating from Kintzele Ditch in the study area is probably small, and constant agitation of nearshore sands by current and wave action keeps silt suspended until it drifts to deeper water, limiting its impact on the shallow, nearshore environment studied here. As with turbulence, siltation from Kintzele Ditch likely did not contribute to changes in the invertebrate community at sampling stations in 2002.

CONCLUSIONS

Two main communities within the nearshore area were apparent in this study. The shallow water benthic community, seen at the 1.5 and 3 m sites, endures nearly constant disturbance by wave action and is dominated by *C. diastrophus* and to a lesser extent Nematoda, and *Paracladopelma* spp. with other less common taxa identified. The deeper community, seen at 6 m sites, is dominated by Nematoda with *C. diastrophus*, *A. leydigi*, and *Paracladopelma* spp. being subdominant and many other taxa identified, and the increased diversity is likely due to an increase in the habitat's stability. A negative impact on invertebrate densities in the nearshore sand community was noted in 2002, and although the precise mode of influence remains unclear, the present analysis suggests that beach nourishment contributed to this effect. Many gaps remain in the understanding of the nearshore benthic community and its response to environmental disturbance, and perhaps this study will prompt further investigation of this dynamic, yet poorly understood ecosystem.

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REFERENCES

- Barton, D.R., and Carter, J.C.H. 1982. Shallow-water epilithic invertebrate communities of eastern Georgian Bay, Ontario, in relation to exposure to wave action. *Can. J. Zool.* 60:984–993.
- , and Griffiths, M. 1984. Benthic invertebrates of the nearshore zone of Eastern Lake Huron, Georgian Bay, and North Channel. *J. Great Lakes Res.* 10:407–416.
- Booth, J.S. 1994. Wave climate and nearshore lakebed response, Illinois Beach State Park, Lake Michigan. *J. Great Lakes Res.* 20:163–178.
- Chrzastowski, M.J., and Thompson, T.A. 1994. Late Wisconsinan and Holocene Geologic history of the Illinois-Indiana coast of Lake Michigan. *J. Great Lakes Res.* 20:9–26.
- Clarke, K.R., and Gorley, R.N. 2001. *Primer v5: User Manual/Tutorial*. Plymouth, UK: PRIMER-E, Ltd.
- , and Warwick, R.M. 1994. *Change in Marine Communities: An Approach to Statistical Analysis and Interpretation*. Plymouth, UK: Plymouth Marine Laboratory.
- Coffman, W.P., and Ferrington, L.C.J. 1996. Chironomidae. In *An Introduction to the Aquatic Insects of North America*, eds. R.W. Merritt and K.W. Cummins, pp. 635–754. Dubuque, Iowa: Kendall/Hunt Publishing Co.
- Colman, S.M., and Foster, D.S. 1994. A sediment budget for Southern Lake Michigan: source and sink models for different time intervals. *J. Great Lakes Res.* 20:215–228.
- DeFelice, R.C., and Parrish, J.D. 2001. Physical processes dominate in shaping invertebrate assemblages in reef-associated sediments of an exposed Hawaiian coast. *Mar. Ecol. Prog. Ser.* 215:121–131.
- Horvath, T.G., Whitman, R.L., and Last, L.L. 2001. Establishment of two invasive crustaceans (Copepoda: Harpacticoida) in the nearshore sands of Lake Michigan. *Can. J. Fish. Aquat. Sci.* 58:1261–1264.
- Hudson, P.L., and Lesko, L.T. 2002. *Free-living and parasitic copepods of the Laurentian Great Lakes: Keys and details on individual species*. Ann Arbor, MI: Great Lakes Science Center. <http://www.glsc.usgs.gov/webkey.main.htm>
- Kathman, R.D., and Brinkhurst, R.O. 1999. *Guide to the Freshwater Oligochaetes of North America*. College Grove, Tennessee: Aquatic Resources Center.
- Nalepa, T.F., and Quigley, M.A. 1983. Abundance and biomass of the meiobenthos in nearshore Lake Michi-

- gan with comparisons to the macrobenthos. *J. Great Lakes Res.* 9:530–547.
- , Hartson, D.J., Fanslow, D.L., Lang, G.A., and Lozano, S.J. 1998. Declines in benthic macroinvertebrate populations in southern Lake Michigan, 1980–1993. *Can. J. Fish. Aquat. Sci.* 55:2404–2413.
- Peterson, C.H., Hickerson, D.H.M., and Johnson, G.G. 2000. Short-term consequences of nourishment and bulldozing on the dominant large invertebrates of a sandy beach. *J. Coastal Res.* 16:368–378.
- Shabica, C., and Pranschke, F. 1994. Survey of littoral drift sand deposits along the Illinois and Indiana shores of Lake Michigan. *J. Great Lakes Res.* 20:61–72.
- SPSS. 1999. *SPSS Base 10.0 User's Guide*. Chicago, IL: SPSS, Inc.
- Thompson, T.A. 1989. Anatomy of a transgression along the southeastern shore of Lake Michigan. *J. Coastal Res.* 5:711–724.
- Thorp, J.H., and Covich, A.P. eds. 1991. *Ecology and Classification of North American Freshwater Invertebrates*. New York, NY: Academic Press, Inc.
- Thorup, J. 1964. Substrate type and its value as a basis for the delimitation of bottom fauna communities in running waters. In *The Pymatuning Symposia in Ecology*, eds. K.W. Cummins, C.A.J. Tryon, and R.T. Hartman, pp. 59–74. Pittsburg, PA: Pymatuning Laboratory of Ecology.
- Whitman, R.L., Andrzejewski, M.C., Kennedy, K.J., and Sobat, T.A. 1994. Composition, spacial-temporal distribution and environmental factors influencing the interstitial beach meiofauna of southern Lake Michigan. *Verh. Internat. Verein. Limnol.* 25:1389–1397.
- Wood, W. 1983. *Beach Nourishment Monitoring Program 1975–1982*. West Lafayette, IN: Great Lakes Coastal Research Laboratory.

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